Test for End Connection Integrity of Metalized Film Capacitors

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Abstract

The wire arc metal sprayed end connections of metalized film capacitors limit their performance for high current discharge applications. We have developed a solid state discharge circuit with integrated current-induced partial discharge detector to evaluate the quality of end connections with a single high current discharge, and we have demonstrated a strong correlation between this test and winding discharge life. Such a test can be very useful to the industry, as if the quality of individual windings can be assured, a large capacitor made from many such windings will have greatly improved discharge performance and reliability.

I. INTRODUCTION

The wire arc metal sprayed end connections of metalized film capacitors limit their performance for high current discharge applications. Because the spray does not connect to the film metallization continuously along the film edge and penetrates to varying depths along the edge, locations of very high current density can occur which can cause large potential drops along the metallization or between the metallization and the wire arc metal spray, resulting in local partial discharge (PD) near peak current. Such PD is caused by high current through the end connection, not high voltage across the winding. If a capacitor winding is placed in an underdamped LRC discharge circuit, the current through the capacitor and voltage across the capacitor are nearly 90^o out of phase, which means that the peak current occurs when the voltage across the capacitor is approximately zero. If partial discharge (PD) is observed near the peak current under these conditions, it must be caused by the discharge current and not the applied voltage and is, therefore, symptomatic of end connection discharge. We describe a test for end connection integrity which can evaluate the quality of end connections with a single high current discharge, and we have demonstrated a strong correlation between this test and winding discharge life.

Metalized film capacitors achieve high energy density as a result of "self clearing", i.e., the formation of a small "clearing spot" of evaporated/oxidized metal around a film breakdown site as a result of which the clearing site can support the applied voltage after breakdown. Thus a metalized film capacitor can be operated at a field closer to film breakdown and fails gradually through capacitance loss after many clearings instead of suddenly, as a result of the first breakdown.

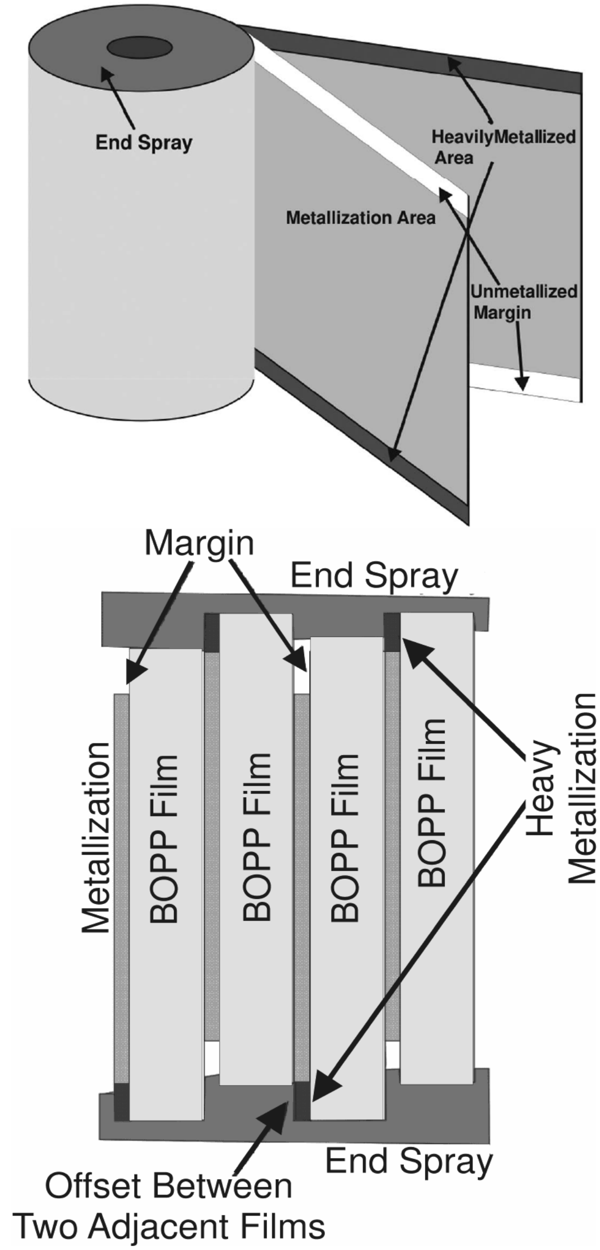

Figure 1. Top, overall structure of a metalized film capacitor. Bottom, cross sectional view of a winding showing the more heavily metalized film edge, lightly metalized active region, and an unmetallized margin. The two film layers are offset so that the heavily metalized region at the top protrudes beyond the layer below. This creates the lose region of "unsupported" film, which is labeled "Edge" in Figure 2.

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14. ABSTRACT
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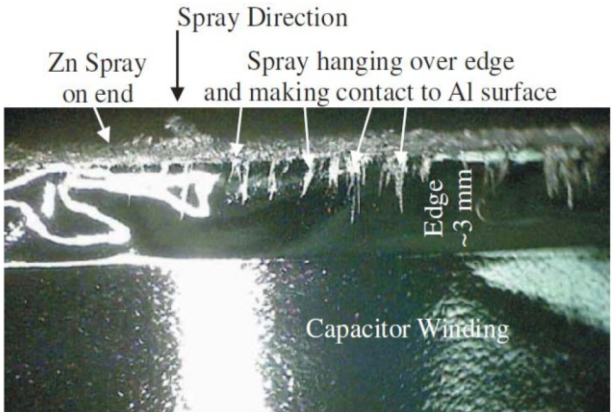

Figure 2. Wire arc sprayed end connections. The wire arc sprayed metal forms many small discontinuous filaments on the surface of the heavily metalized film margin. Current concentrates at the tips of these filaments, especially long filaments with relatively large separation from adjacent filaments.

The development of self-clearing metalized film capacitors (Fig. 1) resulted in a large increase in energy density but a limitation in peak discharge current, as 10 A/m current density along the film edge is considered the limit for stable, long term discharge performance. For some applications of high voltage metalized film capacitors, the desired discharge current density along the film is much greater than 10 A/m [1]. Thus improving end connection integrity is important, and one important step in this direction is developing a non-destructive diagnostic. A diagnostic for end connection integrity can improve the discharge performance and reliability of large capacitors by assuring the "quality" of each winding assembled into a large capacitor,

End connections of metalized film capacitors are usually formed by wire arc metal spray [2]. However, the spray particles are much larger than the gap between capacitor film layers in the end margin region, with the result that the spray "splashes" into the gap between film layers, forming filaments along the metalized film surface, as seen in Fig. 2. Current tends to concentrate at the tips of these filaments, especially where the random separation between filaments is large. High current at the filament tips can cause either loss of contact between the filament and metalized film through thermal phenomena or excessive current and voltage drop near the filament tip, either of which can cause discharge at the filament tips [3]. An excessive distance along the winding edge without connection to the sprayed end connection can also cause discharge between the winding edge and end connection. Thus if current-induced discharge can be detected at the end connection, the end connection quality can be assessed. As noted above, an underdamped RLC discharge results in a 90^o phase shift between the current and voltage, so that peak current occurs near zero voltage. Thus if PD is detected near peak current, the PD must be current induced and not voltage induced.

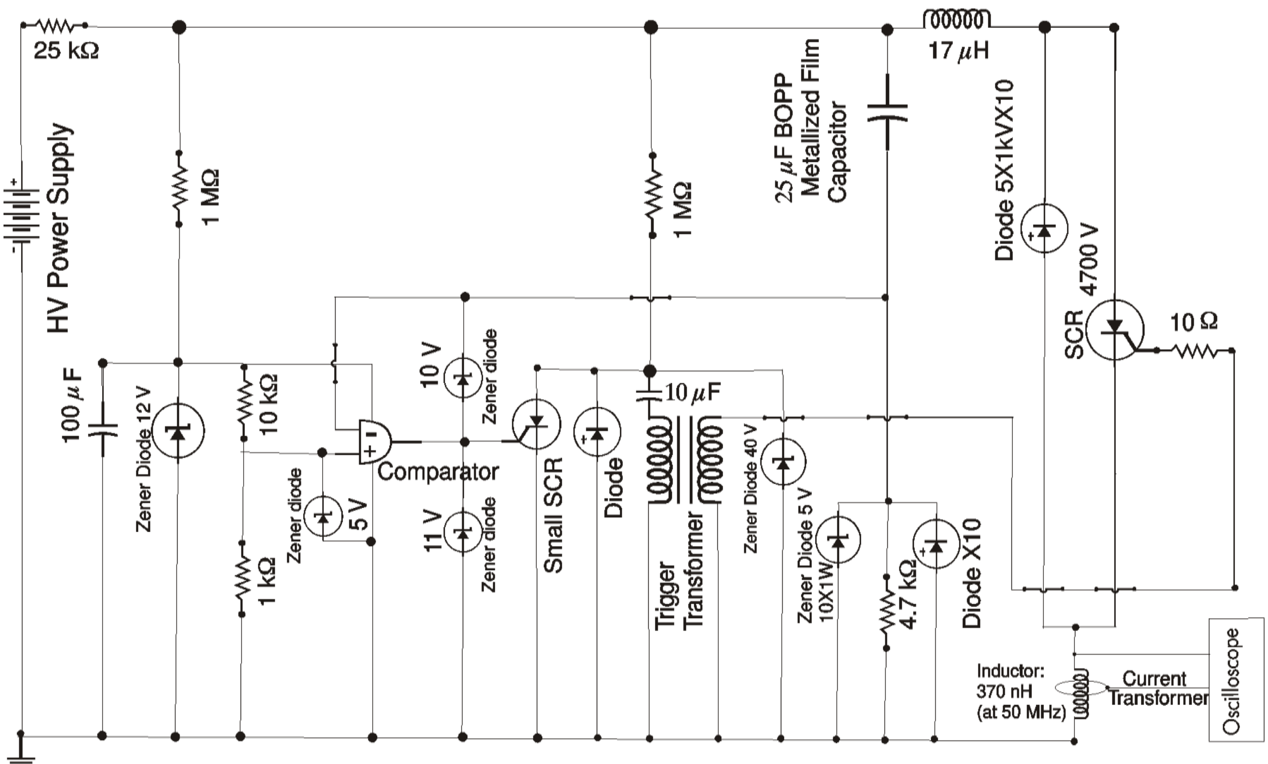

Figure 3. Circuit diagram of the end connection test system. The device under test is the 25 μF BOPP capacitor adjacent to the inductor near the top right of the diagram. The CT (bottom right) measures the discharge current, while the current-induced high frequency PD signal is measured across the 370 nH inductor using a 50 MHz high pass filter between the inductor and 'scope.

II. DEVICE DESCRIPTION

The discharge system (Fig. 3) acts as a “relaxation oscillator” with trigger circuitry which detects when the winding is near full charge, at which point the high current SCR is triggered to discharge the winding under test through the ~17 μH inductor. Diodes are included in to provide a path for reversal of the current during oscillation. The high voltage supply also provides low voltage power for the SCR trigger circuitry so that no low voltage power supply is required.

The SCR trigger circuit consists of a comparator provided with a reference voltage on one input based on a resistive division of the 12 V low voltage supply to ~1.2 V, while the comparator other input is taken from a 4.7 kΩ resistor in series with the capacitor during charging. When the voltage across the 4.7 kΩ resistor drops below 1.2 V (~0.25 mA charging current), the comparator switches and triggers a small SCR which discharges a 10 μF capacitor charged to 40 V through the primary of the SCR trigger transformer, the secondary of which is connected to the trigger input of the high voltage, high current SCR (Applied Pulsed Power Model S38). The LRC discharge of a 25 μF winding results in under damped, resonant discharge (Fig. 4) with frequency in the 10 kHz range. The inductor goes in and out of saturation during discharge, so that the resonant frequency cannot be computed with any precision.

During discharge, the current is monitored using a 3 MHz bandwidth current transformer. To characterize the winding end connection “quality”, high frequency PD induced signals are measured across a 370 nH air core inductor with a self resonant frequency in the 100 MHz range. The voltage drop across this inductor is passed through a 50 MHz high pass filter before being applied to a high frequency oscilloscope with a sampling interval of 2 ns, which is necessary to capture the high frequency discharge signals.

III. PD PATTERNS

A 25 μF and a 6 μF winding were each charged to 1200 V, and the discharge waveforms were recorded as shown in Fig. 4. The discharge periods (*T*) for the two windings are about 66 and 37 μs. By substituting the winding capacitance and the resonant frequency into eq (1) and solving for *L*, we can obtain the effective inductance in the circuit for the two cases, which are 4.4 μH and 5.5 μ*H* respectively, much smaller than the nominal 17 μ*H*, which indicates that the inductor is saturated over much of the discharge waveform with greater saturation from the higher peak current with the 25 μF winding.

$$\frac{1}{T} = \quad = \frac{1}{2\pi} \quad = \qquad (1)$$

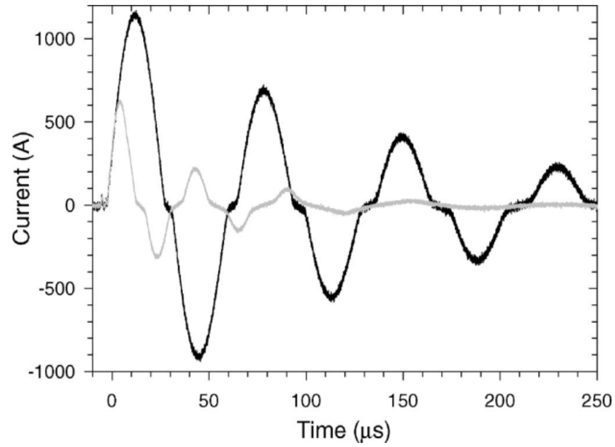

Figure 4. Discharge current vs time for a 25 μF capacitor winding (black) and 6.2 μF (gray) with about 1200 V on the capacitor at discharge. The discontinuities in the waveform are caused by the inductor core going in and out of saturation.

A. PD Patterns of Good Winding

The PD pattern of a winding with good end connections is shown in Fig. 5. For a 25 □F winding with good end connection, little PD can be detected during discharge at about 1100 A peak current (1200 V charge), which corresponds to about 17.5 A/m of film edge. After 50 such discharges, the increase of the PD is small which indicates that if current-induced PD is absent on the first discharge, the end connection tends to be stable at that discharge current density.

B. PD Patterns of Bad Winding

Fig. 6 shows the discharge waveform of a nominally identical 25 μF winding with poor end connections at about the same discharge current. A large amount of PD can be observed near the current peak during the first discharge of the winding. After 50 discharges, a substantial increase of PD is observed, along with a large change in the discharge current waveform caused by increased capacitor ESR as a result of end connection degradation. Thus by observing PD activity within ±30^o of the current peak, we can distinguish, nondestructively, between a winding with good and poor end connections based on a single high current discharge.

IV. DISCUSSION

The correlation of the PD pattern with discharge life was established by objective testing. About 20, 25 μF windings were characterized with the end connection test system after which they were send back to the manufacturer for destructive discharge testing. All the windings which were rated as “good” based on the end connection test system passed the manufacturer’s discharge life test without failure, while all the windings which were rated as “poor” based on the end connection test system failed prematurely during the manufacturer’s

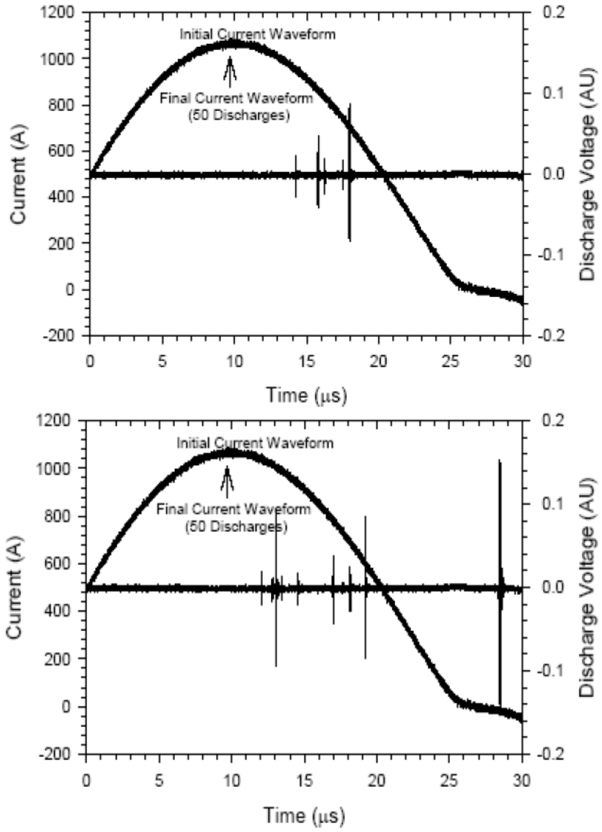

Figure 5. PD pattern (right axis) of a good winding during 1100 A peak discharge current (left axis). Top, PD during first discharge and bottom, PD pattern after 50 discharges, each of which correspond to a peak current density of about 17.5 A/m of film edge. Little PD and no change of discharge waveform is evident after 50 discharges.

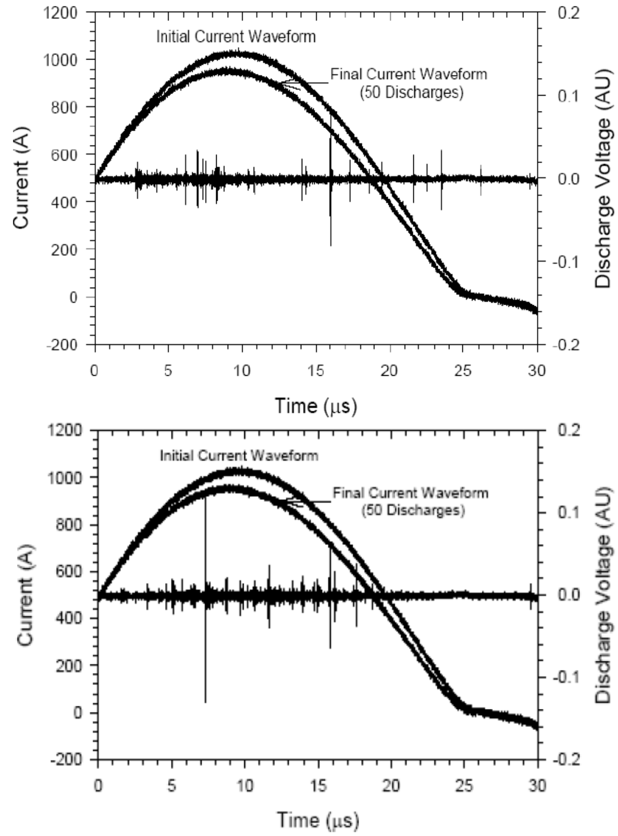

Figure 6. PD pattern of a winding with poor end connections during discharge. Top, first discharge and bottom, PD pattern of the winding after 50 discharges. Substantial increase of PD can be observed after the 50 discharges along with a decrease of peak discharge current caused by increased ESR from the degradation of the end connections

discharge life test. We have developed objective measures of discharge activity by which windings can be characterized, although space does not permit a detailed discussion of this topic. Thus by measuring current-induced PD activity during high current discharge in an LRC resonant circuit, the quality of metalized film end connections can be characterized reliably.

V. REFERENCES

1. Qin and S.A. Boggs. "Limits to the Performance and Design of High Voltage Metalized Film Capacitors". IEEE Trans. DEI, Vol. 17, No. 4, pp. 1298-1306, 2010.
2. W. Reed and S.W. Cichanowski. "The Fundamentals of Aging in HV Polymer Film Capacitors." IEEE Tran. DEI, Vol. 1, No. 5, pp. 904-922, 1994.
3. X. Qi and S.A. Boggs. "Electrothermal Failure of Metallized Film Capacitor End Connections - Computation of Temperature Rise at Connection Spots". J. App. Phys. Vol. 94, No. 7, pp. 4449-4456, 2003.
4. X. Qi and S.A. Boggs, "Transient Finite Element Computation of the Temperature Rise in Metalized Film Capacitor End Connections Caused by Underdamped Discharge", IEEE Trans. DEI, Vol. 15, No. 1, pp. 277-283. 2008.
5. Qi and S.A. Boggs, "Novel Capacitor Discharging System" Review Sci. Inst., Vol. 77, Issue, 8, pp. 084701-084701-5, 2006.